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Monitoring freshwater, estuarine and near-shore benthic ecosystems with multi-sensor remote sensing: An introduction to the special issue

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ABSTRACT

This special issue features 15 papers focused on the use of remote sensing as applied to various aspects of freshwater, estuarine and near-shore benthic ecosystems. The work described herein is diverse, ranging across spatial and temporal scales, and making use of optical, radar and lidar technologies. The need for this applied research has become more crucial by the day, as resource managers are faced with issues ranging from non-point source pollution to wetland destruction, invasive species, climate change and more. Routine monitoring and mapping of the changes taking place in these ecosystems enable managers to focus their efforts in time and space, and to prioritize their responses to the most pressing issues. The most compelling aspect of much of the research reported within these pages is that the best advances emerge from the combined use of technologies across the spectrum (literally) and across a range of spatial and temporal scales. No single issue threatening the health of these ecosystems can be addressed using a single approach or with a single image acquired at a given point in time. Despite the additional resources and expense required to make use of multi-sensor, multi-temporal and multi-scale image data, the utility of such data becomes evident across a diverse range of ecosystems and a wide range of conditions. As such, we view this compilation as useful not only for applied resource management, but also as a compelling contribution to the advancement of both basic and applied research in this subject area.

Freshwater, estuarine and near-shore benthic ecosystems are all under increasing pressure from resource extraction (e.g. fisheries and water use), pollution from land use change associated with growing populations and urban expansion, aquatic and terrestrial invasive species at all trophic levels, and climate-induced changes in the quantity and seasonality of hydrologic flows (Oki & Kanae, 2006). Providing accurate assessments of the pressures placed on these ecosystems is the impetus for this special issue. Management of aquatic ecosystems requires improved monitoring systems to track changes in water quality and quantity through time, but such records are best contextualized using synoptic data that can elucidate processes occurring throughout entire landscapes (see Mertes et al., 2004). Remote sensing provides a means to meet these mapping and monitoring requirements. Optical, radar and lidar sensors and associated processing algorithms (Tatem et al., 2008) have improved freshwater monitoring capabilities and, in turn, an ability to inform management of aquatic ecosystems.

The intent of this special issue is to provide insights into both technology advances and an expanding range of applications that utilize remote sensing to understand aquatic ecosystems across a wide range of scales. Our hope is that the research and case studies presented herein, which capture diverse techniques, ecosystems, and integrative uses of remotely sensed data, will inform technical and management audiences alike. Of the 14 papers, ten focus primarily, albeit not exclusively, on the use of optical remote sensing (Table 1). This emphasis reflects the longer history of optical remote sensing and the utility of shorter wavelength reflectance and absorption properties for aquatic ecosystem monitoring. Two papers focus on radar remote sensing. One reports on the detection and mapping of seasonally inundated wetlands in the coastal plain of the mid-Atlantic USA. The second radar paper demonstrates the utility of interferometric SAR for digital elevation mapping in remote areas of low relief. The final two papers employ lidar remote sensing, one for topographic mapping in areas of low relief and the other for near-shore, marine benthic habitat mapping with visible-wavelength lidar.

Ruiz-Verdú et al. (2008-this issue) compare remote sensing algorithms that target phycocyanin pigments as a surrogate for cyanobacterial biomass. Utilizing *in situ* reflectance data, the authors are confident in algorithm predictions at moderate to high cyanobacterial biomass in eutrophic waters, but they highlight non-linearities that lead to under- and over-estimation errors. Resolving those prediction

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Table 1
Summary of papers in this special issue, categorized according to nominal resolution of data used for analysis, use of multi-date acquisitions, sensor type utilized, targeted ecosystem type, and general objective

Lead author	Grain/ resolution	Multi-temporal	Sensor	Habitat	Process
Verdu	High	Yes	Hyperspectral	Lake	Water quality
Randolph	Ultra-fine	No	Hyperspectral	Reservoir	Water quality
Siciliano	Fine	Yes	Hyperspectral	Estuary	Water quality
Hestir	Fine	No	Hyperspectral	Estuary	Vegetation
Gilmore	Fine	Yes	Multispectral	Estuary	Vegetation
Nielsen	High	Yes	Multispectral	Wetland	Vegetation
Goetz	High	Yes	Multispectral	Stream	Land/water
Olmanson	High	Yes	Multispectral	Lake	Water quality
Gons	Moderate	No	Multispectral	Lake	Water quality
Friedl	Moderate	Yes	Multispectral	Wetland	Water quantity
Lang	High	Yes	SAR	Wetland	Water quantity
D'Ozouville	High	No	InSAR	Stream	Hydrology/ geomorphology
Jones	Fine	No	LIDAR	Stream	Hydrology/ geomorphology
Wedding	Fine	No	LIDAR	Benthic	Bathymetry

errors remains important for monitoring and perhaps ultimately predicting the emergence and expansion of harmful pathogens in aquatic ecosystems.

Also focusing on cyanobacteria, Randolph et al. (2008-this issue) apply and validate a semi-empirical remote sensing method for mapping relative concentrations in turbid inland reservoirs where water chemistry includes high concentrations of phytoplankton, suspended sediments, and fine particulate organic matter. Their approach may serve as a rapid assessment tool for the spatial distribution and relative concentration of blue-green algae.

Siciliano et al. (2008-this issue) explore one such highly eutrophic system, a tidal wetland in California. They assess aquatic vegetation responses to nutrient enrichment and were able to extrapolate local observations to the entire estuarine system using synoptic remote sensing observations acquired by an aircraft-mounted sensor. While extrapolating observations is fundamental to remote sensing practice broadly, this paper introduces *in situ* experimental and observational techniques aimed at freshwater ecosystem monitoring.

In a related study within California's Bay-Delta ecosystem, Hestir et al. (2008-this issue) used hyperspectral remote sensing to detect and map non-native invasive species in different aquatic habitats. By targeting acquisitions to different times of year, they exploited the changes in multispectral reflectance of invasive aquatics with phenology, thereby improving detectability and overall map accuracy. This study reinforces a theme echoed throughout this special issue: multi-temporal observations and careful scheduling of data acquisition improve monitoring by remote sensing.

Gilmore et al. (2008-this issue) describe efforts to map dominant vegetation types in a lower Connecticut River tidal wetland system, especially focusing on invasive *Phragmites* colonies, using a combination of fine resolution QuickBird satellite imagery and aircraft-acquired lidar surface elevation measurements. As with Hestir and colleagues, species-specific mapping was improved through acquisitions that targeted predictable phenological changes in reflectance by targeted plant species. Practitioners will find their fuzzy-accuracy assessment a valuable addition.

The utility of multi-temporal Landsat imagery to detect wetland change in the mid-Atlantic region of the United States is emphasized by Nielsen et al. (2008-this issue) Comparing an image time series to pre-existing National Wetland Inventory (NWI) data and orthorectified photographs, they develop an outlier-detection algorithm to highlight areas where wetlands have been modified by a variety of land cover and land use changes.

Goetz and Fiske (2008-this issue) also used land cover information derived from multi-date Landsat data spanning the mid-Atlantic region, in this case to predict multimetric biotic indices that managers employ to assess habitat and water quality in streams. Their analysis also explored the importance of land cover and land use configuration along overland flowpaths for water. They promote this as a method for assessing the physical linkages between stream health and land cover.

Olmanson et al. (2008-this issue) used Landsat TM and ETM+ data to generate a 20-year water clarity census of Minnesota's lakes and thereby demonstrate the utility of the long-term consistent observations provided by the ever-expanding Landsat image archive, which has recently been opened up to all users at no cost. They are now providing an operational capability for monitoring water clarity, a key indicator of water quality, across thousands of lakes in the state.

At a very different spatial scale, and making use of relatively new moderate resolution (300 m) MERIS imagery, Gons et al. (2008-this issue) map chlorophyll concentrations in two of the Laurentian Great Lakes: Michigan and Superior. They demonstrate the utility of MERIS for chlorophyll mapping across large lake systems but note a need for additional work to better discriminate variability under a broader range of oligotrophic and eutrophic conditions.

Ordoyne and Friedl (2008-this issue) also worked at moderate resolution, making use of the growing database of high temporal frequency MODIS imagery to delineate wetland flooding in the Florida Everglades. They describe a novel technique using MODIS products for dynamic flood monitoring across this extensive wetland system.

The seasonality of flooding in wetland systems was also explored by Lang et al. (2008-this issue), but they make use of multi-temporal, multi-polarization synthetic aperture radar (SAR) imagery to delineate forested (palustrine) wetlands in the mid-Atlantic Coastal Plain. Their results indicate a robust link between the SAR acquisitions and seasonally dynamic hydroperiod in the region.

Because the extent of wetland areas is often delineated by relatively low topographic relief, as was the case in both of the previous two papers, there is a need to better map topography in such areas. d'Ozouville et al. (2008-this issue) utilized interferometric SAR from ENVISAT's ASAR sensor to generate digital elevation models of the remote islands of the Galapagos Archipelago. They demonstrate the utility of InSAR at high resolution as a complement to the widely used but lower resolution Shuttle Radar Topography Mission (SRTM) data sets.

Jones et al. (2008-this issue) also analyze topographic information in areas of low relief, i.e., the swale topography typical of alluvial floodplains. By analyzing high vertical- and horizontal-resolution lidar data acquired from aircraft, they inferred how small terrain features are likely connected at different flood stages. Their methogology elucidates geomorphic controls along the floodplain of the Umatilla River, Oregon.

Finally, Wedding et al. (2008-this issue) used imaging lidar data to measure elements of benthic habitat complexity in a coastal embayment of Hawaii. This paper is unique from the others in several ways, particularly in its focus on benthic marine habitats rather than freshwater or estuarine ecosystems, but also because it makes use of visible-wavelength lidar (rather than infrared or the less common ultraviolet sensors) to map the rugosity of coral reef habitat. This is a field of research that is rapidly advancing with the advent of lidar, and it promises to reveal new information about these threatened ecosystems, particularly when used in synergy with passive optical remote sensing observations.

This set of papers spans diverse applications across a spectrum of spatial scales, makes use of a diversity of sensors (both old and new), and introduces a suite of novel processing and analysis techniques. Collectively, they offer a glimpse of substantive advances that should spur more widespread interest and application of remote sensing for freshwater, estuarine, and near-shore benthic ecosystems. A recent review of best practices for freshwater conservation planning emphasized the importance of remotely sensed data for inventory and assessment, but also noted a lack of ubiquity (Nel et al. in press). In addition to the fundamental principles presented here, such as multi-temporal acquisitions and multi-source assessments, we foresee an increase in data integration ("fusion") technologies, including synergistic use of hyperspectral and lidar sensors (e.g., Asner et al., 2007). Moreover, end-to-end airborne sensor data processing streams are emerging that offer advantages for freshwater ecosystem research such as rapid data turn-around and on-demand flight scheduling. We hope that these technological advances, coupled with the studies presented here, encourage wider use of remote sensing techniques and applications among those who are not remote sensing specialists, including those with responsibilities in aquatic ecosystem management and conservation.

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We dedicate this special issue to the memory of Herman Gons and Leal Mertes, who not only contributed to and co-authored papers contained herein but also, more importantly, were influential figures in their areas of expertise and were instrumental in advancing the knowledge upon which much of this work is built. We owe them a debt of gratitude.

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